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COST ESTIMATION: AN EXPERT-OPINION APPROACH

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This document outlines a methodology which can be used to estimate the costs of research and development projects. The approach uses the Delphi technique—a method developed by the Rand Corporation for systematically eliciting and evaluating group judgments in an objective manner. The use of the Delphi allows for the integration of expert opinion into the cost-estimating process in a consistent and rigorous fashion. This approach can also signal potential cost-problem areas. This result can be a useful tool in planning additional cost analysis or in estimating contingency funds.

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INTRODUCTION

At present three methods are generally used for cost estimating. The "engineering" or "grass-roots" estimating technique makes use of a work-breakdown structure—a hierarchical tree of work elements which comprise the item to be estimated. The cost of hardware and associated labor for each element is estimated and summed to yield total cost. The estimating by analogy approach directly compares the cost of a new item to the cost of a similar item that has already been built and for which cost data are available. The developed item becomes the baseline; that is, the one against which analogies are drawn and judgments about cost are extrapolated. Cost modeling is a statistical procedure that requires a large data base of many similar items. Cost is defined as being dependent on the technical characteristics of the item to be estimated. This relationship is described by a mathematical equation, called a cost-estimating relationship, and is obtained by regression analysis which employs a method of ordinary least squares on the data base. The appropriate parameters of the proposed item are then simply substituted into the equation, the equation is solved, and a cost is obtained.

Although each one of these techniques has certain advantages, they are inadequate for estimating the cost of unique items or those for which old ways of doing business no longer apply. It is in these situations that optimum benefits can be derived from the use of the Quantified Expert-Opinion approach.

DEFINITION

The Quantified Expert-Opinion approach is a combination of two methods—the previously defined analogy estimating and the Delphi process of polling expert opinion. The Delphi technique is a systematic attempt to best utilize group judgment in areas where knowledge is incomplete. The basic premises of this method are that "many heads are better than one" and that a group will be more objective if there is no face-to-face confrontation. A typical Delphi process is run in the following manner. Each participant receives and completes a questionnaire. The identities of the other members are kept from individual members, or, as a minimum, the responses are kept anonymous. A control group then analyzes the answers to the questionnaire and forwards the statistical results of the first trial to the individual respondents so that they can compare their answers to those of the others. The participants at the extremes are asked to write short explanations of their positions, and these are relayed back to the group unsigned. Each participant then has the opportunity to change his or her position. This process is repeated until opinion stabilizes or, if this proves to be impractical, for a predetermined number of times. Finally, the responses are statistically analyzed and aggregated to yield a group response. Experimentation with the Delphi method has shown that, in areas of partial information, it is superior to other methods of obtaining group response. For example, the Delphi approach minimizes the biasing effects inherent in group discussion. In particular it reduces the undue influence of dominant group members, discussion not pertinent to the specific problem, and pressure to conform to majority opinion.

For cost estimating, the Delphi method is used in conjunction with the analogy-estimating technique; that is, the expert opinions are made relative to an item which has been chosen to serve as a baseline. This integration of the analogy and Delphi processes is referred to as the Quantified Expert-Opinion approach to cost estimating.

METHODOLOGY

The Quantified Expert-Opinion approach can be used to estimate the cost of a variety of projects and operations; for example, instruments, spacecraft, or ground operations. Because this approach was first used to estimate the cost of an instrument, instruments will be used as examples throughout this document. The necessary ingredients for the implementation of the Quantified Expert-Opinion approach are: (1) a baseline instrument for which cost data are available, and (2) the availability and cooperation of experts who are familiar with both the baseline and the new instrument.

The Delphi panel members receive a set of questionnaires, one for each program phase. The scope of the questionnaires should be structured to permit the respondent to make a meaningful judgment. Figure 1 shows a typical instrument questionnaire. The participants assess the relative effort by subsystem and program phase for the new instrument as compared to the baseline. In addition to the relative assessment, each respondent also bounds his or her best guess by a high and low assessment for each subsystem. The members return the questionnaires, and the control group analyzes them.

The analysis of the responses can take any of a number of forms. A simple method of showing the responses visually is to graph them as in figure 2. Each triangle (probability density function) mathematically represents one respondent's assessment. The peak of each function is the respondent's best guess, and the points of intersection with the horizontal axis are his high and low bounds. This type of display permits easy identification of extreme opinions. The respondents at the extremes are asked to write short explanations of their positions, and the explanations and the graph are relayed back to the panel members. The panel members now have an opportunity to change their opinions, and the previously

DESIGN AND DEVELOPMENT THROUGH ENGINEERING MODEL

	Relative Effort Assessment	High	Low
Scan mechanism			
Optics			
Coolers and detectors			
Electronics			
Structure and mechanics			

Figure 1. Typical instrument questionnaire.

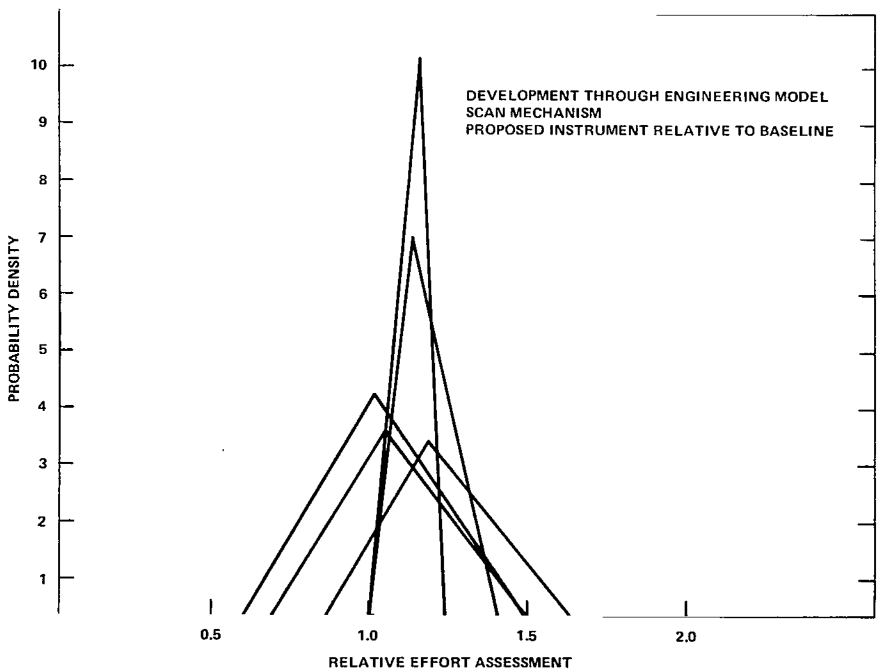

Figure 2. Graph of questionnaire responses.

described process is repeated. This iterative process continues until opinion-changing stabilizes or, if this proves to be impractical, for a predetermined number of times.

The purpose of this analysis is to obtain an average cost and spread for the instrument based on the opinions of the experts. When the final iteration of the Delphi process is completed, the effort-assessment ratios must be translated into cost ratios. This can be accomplished by assuming a one-to-one relationship between the two. In figure 2, note that most of the respondents are grouped around a ratio of 1.10 which means that they think that, at the design and development stage, the instrument's scan mechanism will require 10 percent more effort than that required for the baseline instrument. Assuming that a one-to-one relationship exists between effort and cost, the increased effort translates into 10 percent added cost, and, because the cost data for the baseline instrument are available, the estimated dollar amount is easily obtained. Repeating this procedure and summing over all subsystems and program phases yields the mean total instrument cost estimate. To derive the confidence intervals associated with the mean estimate, further analysis is required. The most convenient case is to assume that the relative effort-assessment ratios are normally distributed and that the subsystems are independent (Appendix A). Utilizing these assumptions, the mean cost for each subsystem could be added to yield a mean cost of the total system, and likewise for the variance associated with each subsystem. The square root of the total variance results in the standard deviation for the total program cost and permits a probabilistic statement concerning the cost estimate. For example, there will be a 68.3-percent probability that the cost of the instrument being estimated will be within one standard deviation of the mean.

Other forms of analysis are dictated when the normality assumption is deemed unreasonable. One approach would be to fit a functional distribution form to the data; another would be to run a Monte Carlo simulation (Appendix B).

SUBSYSTEM SENSITIVITY ANALYSIS

Besides yielding cost estimates, the data obtained from using the Quantified Expert-Opinion approach can also be used for subsystem sensitivity analyses. That is, the data may indicate where additional cost-analysis effort could be most effectively used. The concept is simple: expend additional effort where the uncertainties produce the largest cost spread. For example, consider two subsystems, one at 10 million dollars and the other at 5 million. If the experts are closely grouped on the first subsystem so that their spread is from 9 to 11 million dollars, but widely spread on the second, from 1 to 9 million, it is more important to have the experts concentrate their efforts on improving their estimate on the 5-million-dollar system. In economic terms, the marginal utility of improvements in the estimate are higher in the 5-million-dollar system than in the 10-million-dollar system. Appendix C contains a detailed explanation of this analysis.

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Greenbelt, Maryland May 3, 1976

SOURCES

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2. Parzen, Emanuel, *Modern Probability Theory and Its Applications*, John Wiley & Sons, Inc., July 1970.

APPENDIX A
NORMALITY AND INDEPENDENCE

The data can be analyzed in the following manner using the given assumptions.

First, the data are grouped by subsystem and program phase.

Second, each respondent's modal value (estimate of most confidence) is multiplied by the actual cost of the baseline instrument for the particular subsystem and program phase. For example, if a respondent assessed the design and development effort necessary for the proposed-instrument scan mechanism to be double the effort necessary for the baseline instrument at the same subsystem and program phase level, the actual cost of the baseline-instrument scan mechanism would be multiplied by 2.

Third, the modal cost figures are assumed to be normally distributed with,

$$\text{Mean} = \bar{x}_j = \frac{1}{n} \sum_{i=1}^{n} x_{ij}$$

$$\text{Variance} = \sigma_j^2 = \frac{1}{n} \sum_{i=1}^{n} \left(x_{ij} - \bar{x}_j\right)^2$$

where x_{ij} is the i^{th} respondent's modal cost estimate of the j^{th} subsystem, $\bar{x}_j$ is the mean subsystem cost estimate, and n is the number of respondents.

Fourth, the subsystems are assumed to be independent.

Finally, the assumptions that the modal cost figures are normally distributed in each subsystem and that the subsystems are independent permit us to add subsystem distributions. Consequently, the total cost of five subsystems is normally distributed with,

$$\bar{x}_T = \sum_{j=1}^{5} \bar{x}_j$$

$$\text{Standard Deviation} = \sigma = \sqrt{\sum_{j=1}^{5} \sigma_j^2}$$

where $\bar{x}_j$ is the mean cost for the j^{th} subsystem, $\bar{x}_T$ is the instrument cost estimate, σ_j^2 is the variance for the j^{th} subsystem, and σ represents the error bands of the cost estimate.

APPENDIX B
MONTE CARLO APPROACH

A simulation technique can be used to generate a cost estimate from the relative-effort assessment responses. An empirical distribution of modes, by subsystem, can be derived by sorting them in ascending order and assuming the lowest value to be the lower bound and the highest value to be the upper bound of all responses provided by the individual cost-estimating participants. These values depict the situation in which the relative-effort assessment is thought to be "as high, but no higher than" and, conversely, "as low, but no lower than" the particular values assigned. The distribution function is assumed to be linear between the observed relative-effort assessment ratios, and each of the subsystems are assumed to be mutually independent.

With the help of a computer, the first step in the program is to empirically derive the distribution of each subsystem by program phase and to linearly fit the data. Next, a random number sequence between 0 and 1 picks a value on each respective subsystem distribution and computes the corresponding cost by multiplying the randomly selected ratio of each subsystem by the relevant cost factor and by summing the costs. This process is repeated a large number of times, and thereby generates one cumulative distribution per program phase. This process is repeated for the remaining program-phase distributions yielding a final, total, cumulative distribution, mean, variance, and standard deviation. Typical output resulting from the use of the Monte Carlo approach is displayed in figure B-1.

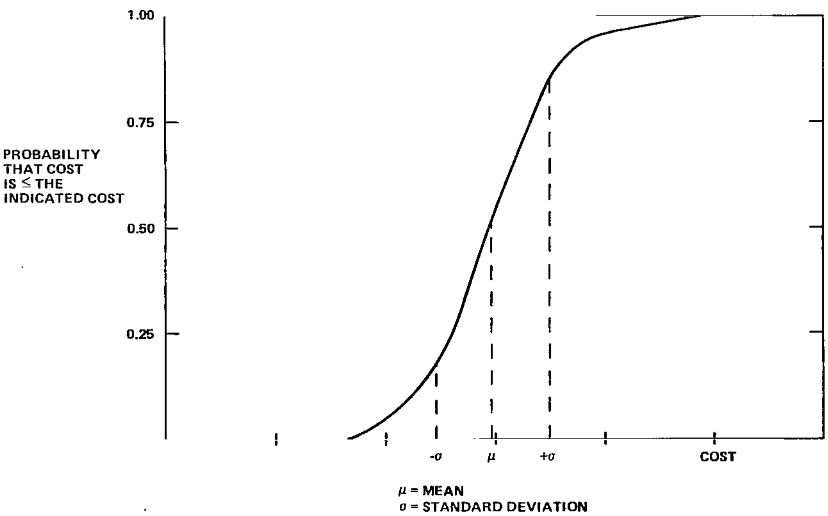

Figure B-1. Estimated cost of the proposed instrument relative to the baseline.

APPENDIX C
SUBSYSTEM SENSITIVITY ANALYSIS

Variance and standard deviation are measures of dispersion. Variance is defined as

$$\sigma_j^2 = \frac{1}{n} \sum_{i=1}^{n} (x_{ij} - \overline{x}_j)^2$$

In this model, σ_j^2 is the variance of the j^{th} subsystem, x_{ij} is the i^{th} respondent's modal cost estimate of the j^{th} subsystem, $\overline{x}_j$ is the mean subsystem cost estimate, and n is the number of respondents. Total variance for the system is simply the sum of subsystem variances:

$$\sigma_T^2 = \sum_{j=1}^{5} \sigma_j^2$$

Standard deviation is defined as the square root of the variance. The standard deviation for the total system gives the cost-estimate error bands and is calculated as follows:

$$\sigma = \sqrt{\sigma_T^2}$$

By definition, the sum of the standard deviations is not equal to total standard deviation. It is therefore impossible to place an exact dollar amount on the change in the cost-estimate error band that is attributable to a reduction of the variance in any particular subsystem.

However, we can measure the responsiveness of the error range to a subsystem change in variance. To show this, take the partial derivative of σ with respect to σ_j,

$$\frac{\partial \sigma}{\partial \sigma_j} = \frac{(\frac{1}{2})(2\sigma_j)}{\sqrt{\sigma_T^2}} = \frac{\sigma_j}{\sigma}$$

The second derivative,

$$\frac{\partial^2 \sigma}{\partial \sigma_j^2} = \frac{1}{\sigma} > o,$$

shows that, as σ_j is reduced, the impact of the reduction on the error band becomes greater ($\partial\sigma/\partial\sigma_j$ is increasing at an increasing rate). That is, efforts to reduce σ_j become increasingly cost-effective.

The marginal effectiveness approach can be used to prioritize the instrument subsystems as to where effort can best be used to reduce cost spread.

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